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## 1. Introduction

Wind vector fields, derived from consecutive water vapor (WV) imagery, are now considered one of the core operational satellite products at the National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite Data and Information Service (NESDIS). NOAA/NESDIS has been deriving WV motion winds from the 6.7 $\mu$ m channel of the GOES-I/M series of satellites in an automated way since 1995. The strength of the WV wind product lies in the fact that it provides coverage in both cloudy and cloud-free environments. The ability to track pure WV structures in clear air provides satellite wind estimates over large areas where conventional cloud-drift winds do not. Furthermore, these clear-air WV winds can provide significantly improved coverage in the middle troposphere where cloud tracers are scarce and often times difficult to track.

The major users of the WV wind products range from the operational analysts and forecasters, who utilize them in a qualitative way during the forecast process, to the Numerical Weather Prediction (NWP) community who make quantitative use of them in the data assimilation process. Their use in NWP is vital, particularly over oceanic areas, for defining the initial state of the atmosphere. Numerous improvements in NWP have been documented as a result of simulating the GOES WV winds. Goerss et al., 1998 and Velden, et al, 1998b, for example, have demonstrated modest improvements in Atlantic tropical cyclone track forecasts during 1995 when GOES cloud-drift and water vapor winds were introduced into the Navy Operational Global Atmospheric Prediction System (NOGAPS).

The GOES cloud-top WV winds are currently being assimilated into the operational regional and global NWP models at the National Centers for Environmental Prediction (NCEP)/Environmental Modeling Center (EMC). The clear-sky water vapor winds are not, however. A major obstacle impeding the use of these winds in data assimilation is the confidence in the heights assigned to these pure WV structures and determining what this motion represents. What are the error characteristics of the height assignments of these pure WV structures? Is the measured motion of these pure WV structures representative of motion at a single level or a layer? Since the radiometric information measured in these cases is emanating from a finite layer, the motion being tracked is almost certainly representative over a layer. But how deep of a layer? How well can these features be tracked in time? Will the answers to these questions explain the characteristic slow speed bias observed in the clear air WV winds, particularly at middle levels of the atmosphere?

The goal of this study is to answer these questions and test new approaches which will, ultimately, improve the quality of the GOES WV winds, particularly under clear sky conditions. Two items which are focused on include feature tracking and height assignment, since these two items can be large contributors to errors introduced to the WV wind product. The errors associated with each of these items will be discussed and characterized in this paper. New approaches aimed at minimizing both of these errors will be presented. In Section 2 we summarize the relevant characteristics of the GOES 6.7 $\mu$ m WV channel. In Section 3, we address the feature tracking technique used at NOAA/NESDIS for estimating motion from WV features and present results which demonstrate the optimal image time interval to use when tracking pure WV structures. In Section 4, we address the height assignment problem for clear-sky WV targets. A new height assignment algorithm, which makes use of the local 6.7 $\mu$ m contribution weighting function (CWF), is tested and validated. Results are presented which characterize the height assignment errors associated with this new height assignment algorithm as well as those currently being used operationally at NOAA/NESDIS. This information should prove useful to the NWP community for assimilating clear-air WV winds into their data assimilation systems.

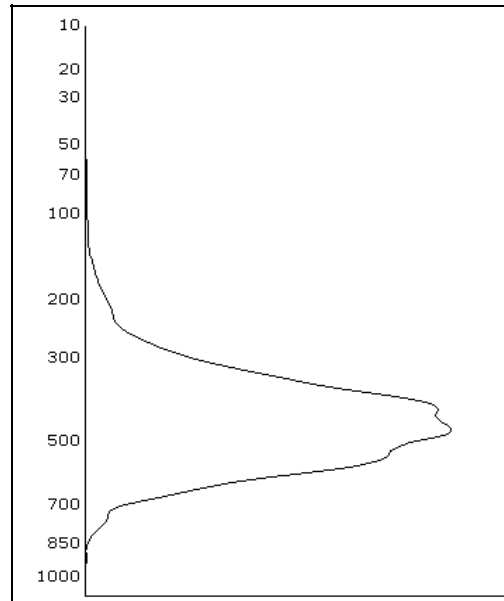
## 2. GOES 6.7 $\mu$ m Channel Characteristics

The GOES 6.7 $\mu$ m channel, which has a resolution of 2.3km (E/W) x 8km (N/S), responds to mid- and upper-level WV and clouds. Because organized atmospheric disturbances usually have large regions of upward (or downward) motion and consequent moistening (or drying), the water vapor data can often be used to locate and define synoptic features such as shortwave troughs, ridges, and jet streams. When animated, this imagery shows atmospheric circulation not always observed in the visible or infrared imagery. This is especially true in areas which are void of clouds where moist and dry air masses can be clearly identified.

In cloud-free regimes, gradients observed in this imagery are indicative of moisture gradients present in the mid to upper

troposphere. These moisture gradients, or pure WV structures, are often conserved through time. This behavior allows for these features to be tracked in time in order to arrive at an estimate of wind motion.

It is clear that a significant amount of information regarding atmospheric motion can be extracted from the 6.7 $\mu$ m imagery. However, the additional piece of information which is needed to further enhance the utility of these data is the height associated with the phenomena being observed. The CWF for the WV channel, using Standard Atmosphere temperature and moisture profiles, is shown in Figure 1. This figure shows that the radiance measured by the 6.7 $\mu$ m channel arises primarily from an atmospheric layer between 200mb and 600mb. Where the peak of the CWF occurs will depend on several factors which include: the presence of clouds, the vertical distribution of temperature and moisture, and the viewing angle of the instrument.



**Figure 1.** Contribution weight function for GOES-8 water vapor channel for the standard atmosphere.

Further discussion of the CWF, its use in defining the heights of pure WV structures, and the impact it has on the quality of the clear-air WV winds is presented in Section 4.

### **3. Water Vapor Feature Tracking: Selecting the Appropriate Image Time Interval**

In the operational NESDIS winds processing system, feature identification and tracking are performed via automated techniques (Nieman et al, 1997, Velden et al, 1997). WV targets are selected, from the middle image of an image triplet, by evaluating bidirectional gradients surrounding each pixel in the 15x15 pixel target array and selecting the maximum value. Once selected, heights of the targets are computed. Further discussion on how these heights are assigned will be discussed in the following section. Once the height is assigned, the feature is tracked in the previous image (backward in time) and the subsequent image (forward in time). Feature tracking is achieved by searching for the minimum in the sum of squares of the radiance differences between the target scene and search scenes.

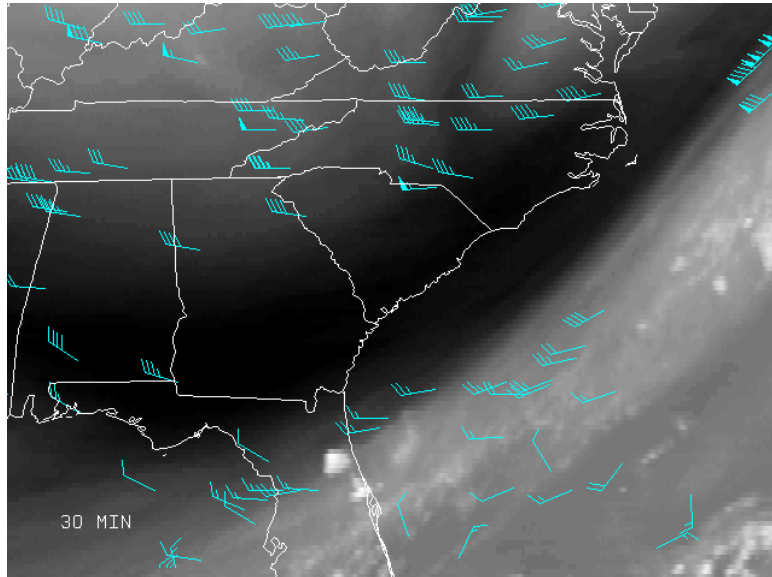
Several factors contribute to tracking errors. These include: resolution of imagery, navigation and registration, low contrast or lack of fine structure in the imagery, and the limited stability of tracers due to non-advective processes. Image resolution and the temporal separation of images used in the feature tracking step are important considerations for deriving high quality wind estimates. The need to have the proper mix of these two variables is well known and documented in previous studies (Jedlovec, 1998).

For the current operational NESDIS WV wind product, the temporal resolution of the images used is 30 minutes. The question is: Is this the optimal time interval to use for clear air WV winds? The coarse resolution (8km) of the water vapor imagery suggests a longer time interval should be used. A longer time interval can be used since the shape of pure WV structures is often more conservative than clouds. Longer time intervals also tend to minimize navigation and

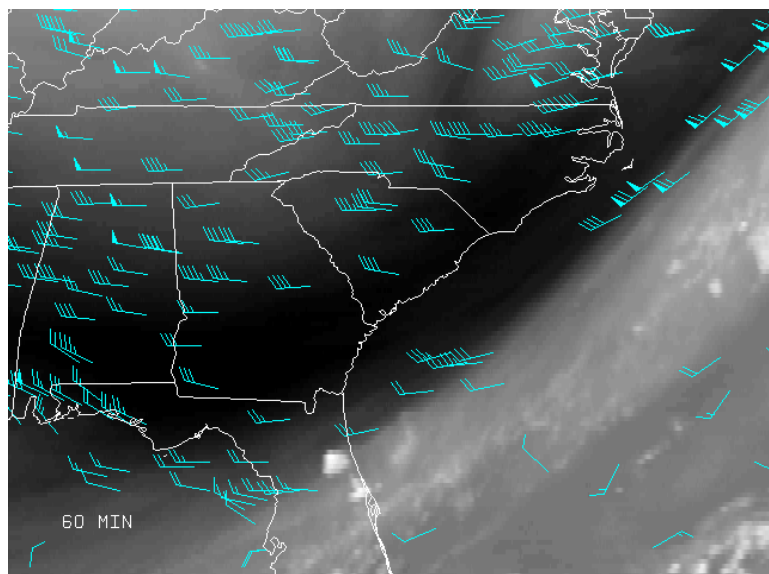
registration errors . Several experiments were run where WV winds were generated and validated using 30-minute and 60-minute interval imagery in order to answer the original question.

Figures 2 and 3 show 30-minute and 60-minute GOES-8 clear air WV winds, respectively, over the continental United States on September 26, 2000. A dramatic increase in coverage is observed. Although not shown in these figures, the most dramatic increase is observed at middle levels (400-700mb) of the troposphere where current satellite wind coverage is lacking. Inspection of clear-air WV wind fields (not shown) prior to the final

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**Figure 2.** GOES-8 Clear air water vapor winds using **30-minute** interval water vapor imagery.



**Figure 3.** GOES-8 Clear air water vapor winds using **60-minute** interval water vapor imagery

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quality control step reveals that the resulting wind fields are more coherent when using 60-minute imagery.

Side-by-side (one using 30-minute interval imagery, the other 60-minute) runs of clear-air WV winds were generated over a period of time and compared to radiosonde winds in order to quantify the impact of using different time intervals on the quality of the satellite winds. Table 1 shows GOES-8 collocation statistics for the 30-minute and 60-minute clear-air WV winds (before final quality control) for the period March 27 - April 14, 2000. Note the dramatic reduction in the mean vector difference, speed bias, and directional difference. These statistics, together with the increase observed in coverage at middle levels of the troposphere, clearly demonstrate that the clear-air WV wind product can be improved if a 60-minute time interval is used. Use of the 60-minute interval imagery, however, results in about a 30% reduction in the number of cloud-top WV winds generated. This was not deemed as detrimental since coverage in the more cloudy regimes is taken care of by the infrared cloud drift winds.

Statistic	30-minute	60-minute
<i>RMS Difference (m/s)</i>	13.61	10.33
<i>Mean Vector Difference (m/s)</i>	11.27	8.78
<i>St. Deviation (m/s)</i>	7.63	5.44
<i>Speed Bias (m/s)</i>	-3.05	-2.15
<i> Directional Diff  (deg)</i>	25.62	20.15
<i>Speed (m/s)</i>	20.06	20.55
<i>Sample Size</i>	8816	8816

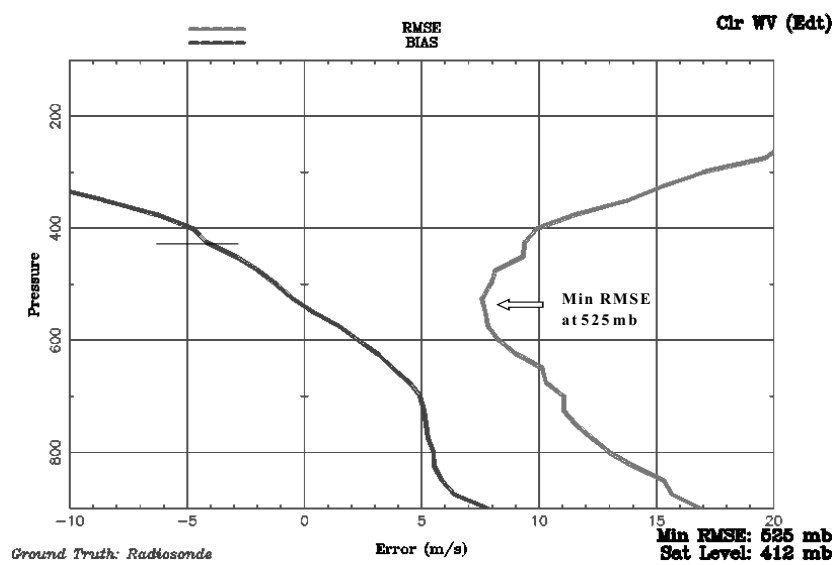
**Table 1.** Collocation statistics for pre-quality controlled 30-minute and 60-minute GOES-8 water vapor winds for the period 3/27-4/14/2000. Radiosondes serve as ground truth.

#### 4. Clear-Air Water Vapor Height Assignment: An Error Assessment

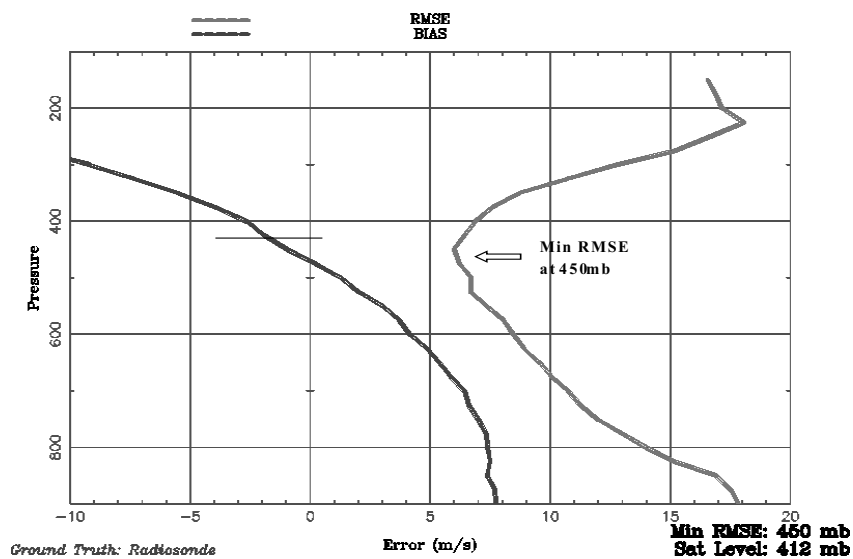
Errors in the height assignment can render a perfectly tracked feature useless to the numerical weather prediction (NWP) community. Furthermore, the representativeness of clear-air WV winds at a single level can be questioned since the radiation sensed by the satellite instrument is emitted from a finite layer. This causes problems for the NWP community when attempts are made to assimilate the data and treat it as a single-level value.

In the current NESDIS winds processing system, measured WV radiances from 5x5 fields of view centered about the clear-air feature being tracked are averaged and compared to a collocated model profile. The height of the feature is then assigned where the satellite and model profile temperatures are equivalent. In this study, a new height assignment scheme which assigns tracer height based upon the CWF is developed and validated. For this height assignment method, model temperature and moisture profiles are used to compute the localized CWF. The height is assigned where the normalized CWF equals 0.75. Characterization of vertical errors for this height assignment method, and the current operational method, are shown below.

To characterize the height assignment errors associated with the clear-air WV winds, root mean square error (RMSE) statistics were generated to include comparisons of the clear air WV winds against all levels of collocated radiosondes. One example of this is shown in Figure 4 which illustrates the accuracy of the satellite winds assigned at 412mb using the operational height assignment algorithm. Figure 5 shows the same thing, but for satellite winds assigned to 412mb using the CWF height assignment. In these figures, the RMSE and speed bias (sat-raob) profiles are shown for a sample of collocations from April-September, 2000.



**Figure 4.** RMSE (m/s) and bias (m/s) for GOES-8 clear air water vapor winds (assigned at 412mb using operational height algorithm) against collocated radiosonde profiles. Bias is satellite - radiosonde.



**Figure 5.** RMSE (m/s) and bias (m/s) for GOES-8 clear air water vapor winds (assigned at 412mb using CWF height algorithm) against collocated radiosonde profiles. Bias is satellite - radiosonde.

Figure 4 illustrates that the clear-air WV winds (those assigned to 412mb in this case) are assigned heights that are too high as the minimum RMSE occurs at 525mb. Note that the magnitude of the RMSE and bias for the water vapor winds at 412mb are about 9m/s and -4 m/s, respectively. Figure 5 shows much better agreement between the assigned CWF heights (again, those assigned to 412mb) and the pressure (450mb) where the minimum RMSE occurs. Note the improved RMSE and bias for the WV winds at 412mb which are about 7m/s and -2m/s, respectively. This kind of analysis was done for WV winds whose height assignments were at other pressures. The statistics for the 412mb WV winds case presented here are somewhat more extreme than the statistics at other pressure levels, but was presented to highlight the potential magnitude of the problem. Table 2 shows the bias (tracer height assignment - pressure where minimum RMSE occurs). Note the reduction in the height assignment bias when heights are assigned via the CWF height assignment method.

Assigned Pressure	Bias (mb) (Opr heights - height of min RMSE)	Bias (mb) (CWF heights - height of min RMSE)
350	-70	-30
375	-55	-5
400-	-60	-20
425	-65	+5
450	-40	+30

**Table 2.** Height assignment bias (tracer height - pressure where minimum RMSE occurs) for operational heights versus CWF heights.

Improved height assignments will improve the quality and utility of the satellite winds. Table 3 shows collocation statistics for mid-level (400-700mb) clear-air WV winds (9/20-10/3/2000) using the current operational height assignment algorithm and the local CWF height assignment algorithm. Note the significant reduction in RMSE and speed bias when heights are assigned using the CWF. In addition, a significant increase in the sample size at mid-levels is observed as the heights of many clear-air tracers are correctly assigned lower in the atmosphere.

Statistic	Opr Heights	CWF Heights
RMS Difference (m/s)	8.10	6.41
Mean Vector Difference (m/s)	6.77	5.41
St. Deviation (m/s)	4.45	3.43
Speed Bias (m/s)	-4.38	-1.23
Directional Diff  (deg)	12.00	11.96
Speed (m/s)	16.53	17.42
Sample Size	493	1051

**Table 3.** Collocation statistics for GOES-8 clear-air water vapor winds generated using the operational height assignment algorithm and the CWF height algorithm for the period 3/27-4/14/2000. Radiosondes serve as ground truth.

## 5. Summary

Satellite-derived clear-air WV winds represent a potentially useful source of information for NWP regarding winds in the middle troposphere. At present, they are currently not being assimilated at the major NWP centers. Results have been presented which indicate that significant improvements in these winds can be realized by improving the tracking and height assignment of WV features. Use of WV images separated by 60-minutes improves the overall tracking. Use of

the local CWF improves the heights assigned to these pure WV features. Together, an improved product is realized.

## **6. References**

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